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VIA CERTIFIED MAIL
RETURN RECEIPT REQUESTED

July 5, 1994

Scientific Officer
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5660

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IN REPLY REFER TO

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Attention: Thomas McKenna

Reference: Contract N00014-94-C-0078

Subject: Progress Report CLIN 0001AA, SBIR Topic No. N93-139
Legged Vehicle for Underwater Mobile Operations

Encl. (1): Progress Report, Jim Jalbert, Northeastern Univ.

Encl. (2): Progress Report, Prof. Joseph Ayers, Northeastern Univ.

Gentlemen:

This letter report summarizes the status of the subject contract. After receiving the contract, Massa Products Corporation and Northeastern University started the work necessary to accomplish the Phase I work effort. This effort consisted of first reviewing the initial status of the design concept. Massa Engineers then proceeded to start work on the preliminary design associated with fabricating a working leg utilizing Nitinol as an actuator. Part of this effort required obtaining a better knowledge of Nitinol. To aid in this Jim Jalbert at Northeastern's Marine Systems Engineering Laboratory did some initial investigations of the properties of Nitinol. Enclosure (1) to this letter is a copy of Northeastern's progress report on these investigations.

Massa Engineers have started a series of experiments to determine how Nitinol wires of different diameters react to different drive currents under various cooling conditions. In parallel with this, some preliminary leg structures have been designed and fabricated in the model shop to determine if the design concepts will allow for Nitinol actuation of the leg joints over the required angular swings. In addition, Massa Engineers have started working with Professor Ayers at Northeastern's Marine Science Laboratory to start the development of the controlling circuits necessary to operate the final leg, which we will fabricate as part of Phase I.

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Professor Ayers has also been developing improvements on the ambulation controller for the robot, and has also been accomplishing a great deal of experimentation on the analysis of Rheotaxic Behavior and Gait Analysis. Enclosure (2) to this letter is a copy of Professor Ayers' first interim progress report describing these efforts in more detail.

Professor Crisman at Northeastern University's Robotic and Vision Systems Laboratory has been analyzing her existing robotic simulation program to determine what variations will be necessary to better simulate the final robot behavior based on the Phase I design efforts. Of particular interest in this revised simulation will be the input of the Nitinol actuators.

At the present time the program is proceeding on schedule, and Massa does not anticipate any problems.

Sincerely,

MASSA PRODUCTS CORPORATION

Donald P. Massa

Donald P. Massa
President

cc: Administrative Contracting Officer
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Northeastern University



Marine Systems Engineering Laboratory

28 June 1994

TO: Don Massa, Massa Inc.
FROM: Jim Jalbert, MSEL/NU
SUBJECT: Progress Report #1 on Lobster Project

This report summarizes technical information gained from an investigation into utilizing SMA actuators as muscle components for the biologically based lobster system to be developed under this project.

Lobster Muscle Actuator Requirements

Contract 2% - 3% of length.
Provide sufficient force to move leg components.
SMA cycle life from hundreds of thousand to millions.
Low power when battery operated in autonomous mode.
Cycle time (contract and relax) fast enough to create walking motion.
Controllable by microprocessor.

SMA Discussion

In order for the SMA actuators to be of value in controlling leg motion of the lobster they must be able to contract and relax in a controlled manner much like muscles. SMA wires made of Nitinol do contract when heated and relax when cooled. The heating mechanism in this application is directly related to current density passed through the wire. Wires can be made to contract up to 8% of their length, however, at this percent contraction the cycle life of the wire will be measured in tens of cycles. If a large number of cycles are required, as in our application, the contraction should be limited to about 3%. This can provide a cycle life of millions provided that proper protection from overstressing, overstraining, and overheating are designed into the system. Another way to increase system cycle life is to use several wires in parallel but to activate them sequentially thus providing a cycle life which is increased by the number of wires in parallel.

SMA contraction time can be quite fast (0.1 seconds or less) depending on the current pulse amplitude and width. Cycle times as fast as 10 - 20 msec have been reported by investigators [C2, C2], however when this is accomplished with very high current values, the cycle life tends to diminish. The relaxation (expansion) time, however, is controlled by the rate of heat loss from the wire. There is great variation in relaxation time with cooling methods. Table 1 presents some relative effects of cooling methods on speed of relaxation [R1].

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TABLE 1

<u>Cooling Method</u>	<u>Improvement in Speed</u>
Increasing stress	1.2:1
Using higher temp. wire	2:1
Solid heat sink material	2:1
Forced air	4:1
Heat conductive grease	10:1
Oil Immersions	25:1
Water with Glycol	100:1

These speed improvements are not accumulative, however, when used together. A very important consideration when using cooling methods for speed improvement is that a significant penalty is paid in power requirements. For example [R2] when SMA wires were used to create a compliant wing section to generate foil curvature the power requirement in air at 22 deg. C was about 15 watts, and when placed in water at 20 deg C. the power required increased by a factor of about 5 for the same wing deflection. It will therefore be essential to tradeoff speed versus power for any application. Another way to increase speed is to use several smaller diameter wires (to achieve sufficient force) in parallel since smaller wires cool faster due to a higher ratio of surface to mass.

Wires can be fabricated which operate at various transition temperature ranges from 100 deg C to cryogenic temperatures. It may be important after experimentating with wires under various cooling conditions expected to select wires which operate at optimum temperatures for ocean application. It may be that we want to utilize wires with lower transition temperatures for in water application to minimize power requirements while still maintaining sufficient cycle time speed.

SMA wires are very strong relative to their size. A 4% contraction can exert stresses of 25,000 psi. Tables which show maximum pull forces versus wire size as well as recommended bias forces, physical and electrical properties can be found in references [R3, R1].

SMA Actuator Control

Control of each actuator requires that current pulses of proper amplitude and duration be applied at the correct times in order to not overheat the wires, and to operate the wires in the correct temperature region near the transition temperatures. This can be considered the lowest level controller of the lobster system. Other higher levels of control are required to direct leg sequence movements and speeds depending on motion type desired.

Proper control of SMA wires for this application will require sensory feedback. Some potential sensory feedback mechanisms are summarized in Table 2.

TABLE 2

Potential Sensory Feedback Mechanisms

Joint or leg Position
SMA wire temperature
SMA wire resistance change

Most investigators to this point have utilized position feedback almost exclusively because this is the easiest to measure. Ideally, wire temperature feedback combined with position feedback would be optimum, however, providing temperature of such small wires has been problematic. We will continue to investigate this possibility. Temperature feedback is important in order to provide sufficient current density to operate the SMA devices near the transition temperatures to prevent overheating them and to maximize response speed regardless of the changes in the environment. As discussed above, the environment has dramatic impact on power level requirements and cycle speeds.

SMA wires also exhibit a change in resistivity (increase) as they transition from the Martensite phase (relaxed) to the Austenite phase (contracted). Flexinol for example is specified to have a resistivity increase of approximately 20% between low temperature and high temperature states. Several investigators have been working on measuring and utilizing this change as a possible feedback mechanism but without much success to date. The resistivity also appears to change with the life of the wire and this is not well understood as yet.

Contacts and References

A list of references and contacts are presented below. Much valuable practical information has been acquired in discussions with investigators who have had experience in trying to apply SMA technology to specific applications.

SMA References

R1 "Technical Characteristics of Flexinol", Dynalloy, Inc. Irvine, ca. received 3 June 1994.

R2 "A Compliant Wing Section for Adaptive Control Surfaces" B.J. McLean et al. Martin Marietta, Denver Co., Paper presented at the SPIE Conf. on Active Materials and Adaptive Structures. Session 16, 1992.

R3 "Motorless Motion, Working with Shape Memory Wires", Roger Gilbertson, Mondo-tronics, 1992.

R4 "Smart Materials: Creating Systems that React", Tim Studt,

R&D Magazine, April 1992

R5 "Shape Changing Metals", Charles Ostman, Emerging Technology, Sep-Oct 1992

R6 "How Shape Memory Metals Shape Product Designs" Robert N. Boggs, Design News, June 1993

R7 "Modeling of a Shape Memory Integrated Actuator for Vibration Control of Large Space Structures", B.J. McLean et al, Martin Marietta Space Systems from Proceedings of US Japan Workshop on Smart/Intelligent Materials and Systems March 1990, Honolulu, Hawaii.

R8 "Development of a Shape memory Material Actuator for Adaptive Truss Applications", B.J. McLean et al, MM Same conference.

R9 "Cambered Flexible Control Fins" C. Beauchamp et al, NUWC, Newport RI., Symposium Flow Noise Modeling, Measurement, and Control, American Society of ME, Winter Meeting Nov-Dec 1993, New Orleans, La.

R10 "Shape Memory Alloy Articulated (SMAART) Control Surfaces", Richard Nadolink, C. Beauchamp, NUWC, Newport RI, no date. received from Charlie Beauchamp.

R11 "Shape Memory Alloy Adjustable Camber (SMAAC) Control Surfaces", Richard Nadolink, Charles Beauchamp, NUWC, Newport RI, no date. received from Charlie Beauchamp.

R12 "Designing With The Shape Memory Effect", T.W. Duerig, K.N. Melton, Raychem Corp, MRS Int'l. Mtg. on Adv Mats. Vol 9, 1989 Materials Research Society.

R13 "Using Shape Memory Alloys", Darel E. Hodgson, Shape Memory Applications Inc., 1988

R14 "Experimenting With Shape Memory Alloys", John Iovine, Popular Electronics, June 1993.

R15 "Shape Memory Applications, Inc. brochure on materials and services from Daryl E. Hodgson, President.

R16 "Introduction to Shape Memory Alloys" TINI Alloy Company, San Leandro Ca. Services, properties, catalog, components, and prices.

Other References

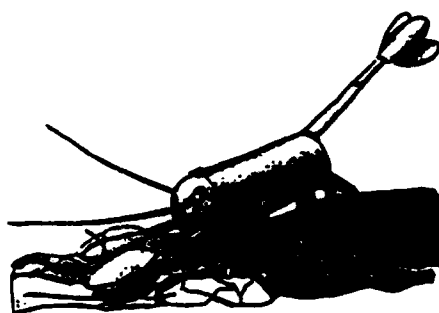
R17 Papers from DCC Corporation, Joseph Marshall: "Hotspot" portable thermocouple welder, "Make your own Thermocouples", "Hotmux temperature Data Logger", and price list.

R18 Information on Lexan products from GE Plastics Pittsfield Ma.

R19 Information on urethane products from Cadillac Plastics, Londonderry, NH.

List of personal contacts:

- C1 Shaw, Phil Oak Tree Automation 703-751-3422
Developed fishlike ROV with SMA wires. Used much power because of cooling system. Also developed prosthetic arm and hand with 36 actuators. Recommended compression fit terminations. good info: see notes
- C2 Hunter Ian, MIT ME Dept. 617-253-3921
developed process for faster responding Nitinol. Spoke to him on 14 jun will call and meet with him in early July. He is just moving in to MIT. Has patents pending on process to get fast response wire.
- C3 Beauchamp, Charles, & Nadolink, Richard NUWC 401-841-2044
worked on cambered flexible control fins (SMA wires) sent several papers and provided other contacts.
- C4 Brown, Wayne Dynalloy 714-476-1206
manufacture Flexinol wires: info on resistivity change and problems; Knows of no direct temp feedback so far. see data sheets, prices
- C5 Hodson, Darrell Shape Memory Applications 408-730-5635
president, company sells SMA material, also mfg components in various shapes, and engineering; see papers
- C6 Gilbertson, Roger Mondo-tronics 415-455-9330
wrote small book on Nitinol experiments, good book for practical use of nitinol. includes some circuits and ideas. see notes and book.
- C7 Johnson, Dave Tini-Alloy 510-483-9676
doing thin film development: actuators, kits, designs etc. see papers and notes
- C8 Marshall, Joseph DCC Corporation 609-662-7272
president, develop temperature measurement products see notes, data sheets.



Memorandum

To: Don Massa
 From: Joseph Ayers
 Date: June 29, 1994
 Re: Ambulatory Robot Interim Progress Report

Development of Ambulation Controller

I have continued development of the biologically based ambulation controller to begin implementation of integrated behaviors with the goal of establishing current and surge adaptations, navigation, compensatory reflexes to gravity and searching. The following new modules have been implemented:

- AntiGravity Recruiter - Allows recruitment of depressor for pitch and roll compensation.
- Sensor Objects - I have integrated a new data structure which corresponds to the labeled-lines of crustacean sensors
- Roll Pitch and Yaw Control - Three new command structures have been implemented which respond to sensor input and evoke adaptive reflexes for antigravity recruit in the pitch and roll planes as well as steering for forward and backward walking in the yaw plane.
- Sequencer - This is a queue structure for sequencing components of behaviors such as reflexes, modal actions patterns and goal oriented behaviors. It is essential for the implementation of complex behaviors such as searching, rheotaxis, etc.
- Modal Action Patterns - I have implemented several "modal action patterns" for various types of collisions based on input from antennae and tail touch receptors.

Analysis of Rheotaxic Behavior

Lars Schlichting and I have implemented the infrastructure for analysis of water current and surge compensation in lobsters and performed preliminary video analysis. Tasks performed to date include:

- **Motion Analysis Extensions to ColorImage:** I have added software objects to my motion analysis program ColorImage necessary for the complex reverse kinematic analysis of rheotaxic behavior. In particular, I implemented a set of algorithms for acquisition of complex display lists. The program now allows one to input up to 15 angles, positions or distances between two points for each of the frames of a video. The results are saved in a table file where the first column is the time of each frame and the subsequent columns are the measured parameters
- **Laminar Flow Tank Implemented:** We have adapted an existing high velocity laminar flow tank to test rheotaxic behavior. The tank includes an arena with a sand bottom and laminar baffles which constrain the specimen to the area of the video image. The tank can produce flow velocities ranging up to 1 m/sec.
- **Wave Surge Tank Implemented:** We have implemented a wave surge tank based on an oscillating pane which replicates well conditions during wave action. We will also be performing underwater video of specimens navigating in the surf zone at Nahant Beach for comparison.
- **Three Dimensional Video System Implemented:** We have implemented a video system which allows us to tape specimens simultaneously from the side and above during maneuvers in the laminar flow and wave surge tanks. The system includes two high resolution (~600 horizontal lines), a SMPTE time code generator and a frame splitter which puts the images from both cameras on one NTSC frame and a High-8 Video Recorder.
- **Initial Video Analysis Performed:** We have developed a marker system consisting of an array of small white beads which are positioned at the articulations of all the major limb joints which will serve as coordinates for digitization of movements. We have optimized the optics and have generated several videos which are available for your inspection.

Gait Analysis

I discovered a new technique of movement analysis on my May trip to Germany which permits acquisition of the position of the limb tip of all eight legs at once. This technique will permit rapid establishment of the gait patterns underlying

walking in the lateral and backward directions which are at present poorly characterized.

- **Lobster Treadmill Implemented:** We have resurrected my original lobster treadmill which I developed at the University of California in the '70s and have developed a new walking balance which will permit us to shift from forward and backward walking to lateral walking.
- **Multi-Leg Movement Transducer Under Development:** Al Badger is developing a version of the 8 leg movement transducer which I discovered in Germany. Basically the system consists of two grid electrodes which are placed at either end of the treadmill tank. A 1 volt 10 khz signal is passed between these grid electrodes. A sensing electrode is attached to the tip of each leg. This system essentially forms a voltage divider so that as the limb moves the output of the sensor electrode is rectified and filtered to generate a DC voltage proportional position of the limb tip between the two grid electrodes. Since a common source signal is used, eight legs can be monitored at once. During forward and backward walking the system can monitor the protraction (swing phase of forward walking) and retraction (stance phase) movements of the limbs. During lateral walking the system monitors the extension and flexion movement. We will record these movements with our SuperScope digital oscilloscope program and establish the intersegmental and contralateral phase lags for forward, backward, lateral leading and lateral trailing walking.